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Challenges in High Energy Density Physics: Plasma Physics in the 21st Century

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Introduction

The purpose of this white paper is to provide a framework for understanding the role plasma physics issues are expected to play in successful ASC Predictive Science Academic Alliance Program (PSAAP), and to identify areas of particular interest and relevance to the NNSA Laboratories. The ASC Predictive Science Academic Alliance Program seeks large scale projects that require the successful integration of these plasma physics areas in a "multi-physics"' framework.

Matter in the plasma state spans a wide range of physical regimes and phenomena including metals, the core of the sun, brown dwarfs, space plasmas, magnetic and inertial fusion. Specifically, high energy density plasmas, which are of critical importance to the NNSA National Labs, are a subset of plasmas that require an understanding of matter at extreme conditions. High energy density plasmas typically involve complex processes that take place over a wide range of length and time scales. Depending on the specific application, accurate descriptions require detailed understanding of processes that include dynamic screening, particle correlations, external fields, radiative transfer, and thermonuclear reactions. Due to the complexity of the plasma state and the desire to make large multi-physics simulations tractable, computational physicists at the National Laboratories have had to make a number of assumptions to model these and other aspects of high energy density plasmas in the ASC radiation-hydrodynamic codes. Sometimes, these assumptions are based on good physical judgment. In other cases, however, there exists a lack of theoretical and/or experimental information to help guide approximations. It is hoped that the science developed at successful ASC PSAAP Centers will elucidate these approximations.

This white paper is closely coupled to the Particle Transport white paper, and both white papers should be read as a pair.

Plasmas and High Energy Density Physics

The working definition of high energy density (HED) that will be used in this paper is taken from the report "Frontiers for Discovery in High Energy Density Physics" prepared by the National Task Force on High Energy Density Physics [1]. High energy density refers to energy densities exceeding $10^{11}\,J/m^3$, or equivalently to pressures in excess of 1Mbar. Alternative characterizations of HED include electromagnetic wave intensities exceeding $3\times10^{15}\,W/cm^2$, or static magnetic fields exceeding 500 Tesla.

The ratio of potential energy to kinetic energy is also a useful parameter for categorizing plasmas. The so-called ion-ion plasma coupling parameter is defined by

$$\Gamma = \frac{Z^2 e^2}{kT}(4\pi n/3)^{\frac{1}{3}}$$

representing the ratio of average potential energy (Z^2e^2/a) to average kinetic energy (kT) for charge Z particles separated by an ion sphere radius a. Weakly coupled, near ideal plasmas correspond to $\Gamma << 1$. Plasmas in this regime have weak particle-particle correlations and are dominated by thermal properties. This is the regime populated by magnetic fusion studies and by portions of the laser-plasma target phase space.

Moderately coupled to moderately-strongly coupled plasmas are characterized by $\sim .1 < \Gamma <\sim 10$ and $\Gamma >\sim 10$. These so called nonideal plasmas exhibit behavior very different from the weakly coupled plasmas discussed above. In this regime, particle-particle correlations are important. Moderately and strongly-coupled plasmas are a difficult to treat theoretically because standard approximations and expansion methods breakdown. These regimes are populated by high intensity laser-matter or pulsed power targets at higher densities or if high Z dopants present, as well as in the cores of giant planets.

Moderate to strong coupling, as well as high densities drive far ranging effects in plasmas because strong ion-ion and electron-ion correlations cause dynamical structures that can affect important atomic, radiative, and nuclear processes in the medium [2]. Equations governing radiative and collisional rates, energy exchange and reaction rates are all altered in this environment.

Figure 1 shows the density-temperature space of some representative plasmas along with iso-contours of ion-ion coupling for a hydrogen plasma (Z=1). Also shown are iso-contours of number density multiplied by the electron or proton thermal deBroglie volume. These help distinguish electron and proton degeneracy regimes. Shown in figure 1 is the density-temperature phase space spanned by hot and warm dense matter. Each of these plasma types will be discussed next.

Hot Dense Matter

Applications as widely varying in scale from laboratory, transient, dense laser-plasma experiments to the cores of stars involve understanding the complex processes present in hot dense radiative plasmas (HDR). The temperatures in HDR plasmas range from a few hundred eV to tens of keV. This extreme state of matter combines atomic, radiative, and even thermonuclear processes where relevant, in highly nonlinear ways. The interaction of these aspects can greatly magnify uncertainties in understanding and predicting the behaviors of hot dense matter.

HDR plasmas of interest to the NNSA National Laboratories typically have the following complicating properties:

- Multiple species of disparate elements.
    - Low Z ions (e.g. p, D, T, He3...)
    - High Z ions (e.g. C, N, O, Cl, Xe, and higher Z)

- Separate temperatures for ion species, electrons, and radiation

- Thermonuclear burn
    - Low Z reactants with or without the presence of high Z dopants
    - High Z reactants (stellar cores)

- Atomic processes (listed below is a sample)
    - Inverse bremsstrahlung
    - Photoionization
    - Line absorption
    - Electron impact ionization
    - Continuum lowering
    - Many body effects on spectral line profiles

- Radiation field propagation in the presence of emission, absorption, and scattering

- Partially degenerate electrons

An important aspect of HDR plasmas is that the photons interact strongly with the medium. The plasma itself will emit, absorb and scatter photons. The radiation field contributes to the overall hydrodynamic motion of the plasma through a large radiation pressure. For temperatures of the order of a keV or greater, which is expected in some laboratory plasmas and at the core of stars, the radiation field becomes the dominant transport mechanism for energy and momentum in hot dense plasmas. Hence, accurate treatment of plasma behaviors depends critically on the photon transport algorithm.

What are some of the issues facing HDR plasmas? An otherwise weakly coupled plasma doped with high Z material can exhibit all the behaviors of a moderately to strongly coupled plasma because the ion-ion plasma coupling parameter depends on the square of the effective ionization. The effects of a nonideal environment on plasma thermalization properties and thermonuclear reaction rates continues to be studied theoretically [2] and is beginning to be studied computationally. In order to improve predictive capability, the National Laboratories will require a detailed understanding of thermonuclear reactions, charged particle slowing down, energy and momentum exchange processes in dynamic nonideal HDR plasmas, through theory and simulation. One avenue is to use molecular dynamic simulations to validate existing approximate models of thermalization.

Warm Dense Matter (WDM)

Warm dense matter physics has received a lot of attention in recent years [2,5] due to the challenges it poses for both experimentalists and theorists. Plasmas in this regime tend to be strongly coupled and therefore have all the properties described above. Cold dense plasmas such as the cores of giant planets are warm dense matter prototypes. Other examples include the behaviors of targets under irradiation by short pulse lasers at intensities under 10^{13} watts/cm^2 Many of the issues relevant to WDM focus on equations of state and transport (conductivity).

Dusty Plasmas

Simply put, dusty plasmas are a many-body collection of charged particles that contains charged microscopic particulates. The presence of these charged “dust grains" can have important effects on the nature of the plasma by introducing new types of instabilities and waves. What role the existence of charged micro sized grains might have in HDR plasmas is relatively unexplored. The presence of small particulates ("dust") in a plasma can change the physical environment in significant ways. For example, if the plasma is cold and only weakly ionized, it is considerably easier to knock electrons off the dust particles than it is to ionize a background neutral atom and thus significantly increase the ionization state of the plasma. Generally in the presence of a plasma, the particulates collect background ions and electrons, become charged, like small Langmuir probes, and modify the charge balance in the plasma. The charged dust particles interact with the background plasma species, with each other and with walls and other conductors. The principal issues in these so called dusty plasmas are related to the various mechanisms by which the dust grains charge, the resultant forces on the grains and their transport through the plasma [6]. The grains can charge to very large values (e.g., a one micron radius particle in a one eV plasma can acquire a net charge of several thousand electrons) and if the density of such grains is large enough, their Coulomb coupling parameter Γ can easily exceed 100. Indeed, for $\Gamma \geq\sim 170$, grains can form into a crystalline state, as has been often observed experimentally. Most of the experimental studies, and related theory of dusty plasmas, have dealt with low temperature, low density rf discharges and extensions to astrophysical systems. There has been some recent interest in particulates in higher density and hotter plasmas, e.g., for magnetic fusion applications [7]. The Laboratories are interested in understanding how the physics of dusty plasmas is modified in these higher energy density regimes and how such processes could be studied theoretically, experimentally and computationally.

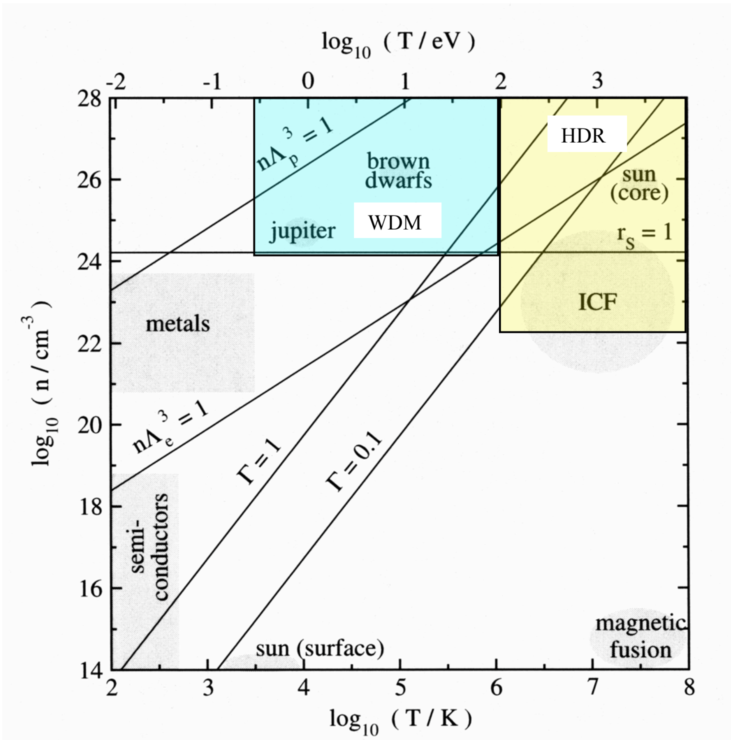

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Figure 1: Density temperature diagram for various common plasmas. The gamma curves are for a pure hydrogen plasma. [2]

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References

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